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Adaptive Boiler Controls: Market Survey and Appraisal of a Prototype System

by
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Many of the Army's boilers have original, outmoded controls and problems associated with code compliance, efficiency, reliability, and availability of spare parts. With uncertain future base requirements, aging equipment, and constrained budgets, a strategic direction is evolving to selectively refurbish boilers that meet minimum mechanical standards. The refurbishing of boilers will include installation of contemporary control systems.

Because of the rapid advance in computer and electronic technologies accompanied by substantial reduction in manufacturing costs, retrofitting outdated control systems with state-of-the-art hardware and software could be cost effective. Adaptive controller technologies are suitable for application under a wide variety of operating conditions. This report documents the results of a market survey of adaptive controllers applied to boiler controls. Various adaptive controller technologies are briefly discussed. Costs and system application information were collected from widely recognized vendors. The performance and cost estimates of a U.S. Army Construction Engineering Research Laboratories/University of Illinois (USACERL/UI) developed prototype system also are presented for comparison. This prototype system was tested on a gas-fired boiler at the UI power plant. Based on the market survey, the prototype system appears to be cost competitive with other surveyed products and warrants further research and long-term demonstration to gain acceptance in the DOD community.

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13. ABSTRACT (Maximum 200 words)
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Because of the rapid advance in computer and electronic technologies accompanied by substantial reduction in manufacturing costs, retrofitting outdated control systems with state-of-the-art hardware and software could be cost effective. Adaptive controller technologies are suitable for application under a wide variety of operating conditions. This report documents the results of a market survey of adaptive controllers applied to boiler controls. Various adaptive controller technologies are briefly discussed. Costs and system application information were collected from widely recognized vendors. The performance and cost estimates of a U.S. Army Construction Engineering Research Laboratories/University of Illinois (USACERL/UI) developed prototype system also are presented for comparison. This prototype system was tested on a gas-fired boiler at the UI power plant. Based on the market survey, the prototype system appears to be cost competitive with other surveyed products and warrants further research and long-term demonstration to gain acceptance in the DOD community.

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Foreword

This study was conducted for the U.S. Army Center for Public Works (USACPW) under Project 4A162781AT45, "Energy and Energy Conservation"; Work Unit EA-X22, "Central Plant Controls." The technical monitor was Philip Conner, CECPW-FU.

The research was performed by the Fuel and Power Systems Team, Energy and Utility Systems Division (FE), Infrastructure Laboratory, U.S. Army Construction Engineering Research Laboratories (USACERL). The USACERL principal investigator was Dr. Mike C.J. Lin. Steven Warner is with Stanley Consultants, Inc., and Yaoxin Qian is with the Department of Industrial and Mechanical Engineering, University of Illinois at Urbana-Champaign. Donald F. Fournier is Acting Chief, CECER-FE, Dr. David M. Joncich is Acting Chief, Infrastructure Laboratory. The USACERL technical editor was Agnes E. Dillon, Information Management Office.

Special acknowledgment is given to the following University of Illinois Abbott Power Plant personnel for their support and cooperation in testing the prototype system: Daniel Dancey, Donald Fortik, Donald White, and other instrument technicians and boiler operators.

LTC David J. Rehbein is Commander and Acting Director, USACERL. Dr. Michael J. O'Connor is Technical Director.

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1 Introduction

Background

Many of the boilers at U.S. Army installations throughout the world have original, outmoded controls and problems associated with code compliance, efficiency, reliability, and availability of spare parts. In general, boilers were designed to operate most efficiently at or near capacity. But today, with consolidation and downsizing of Department of Defense (DOD) bases, many boilers are operating at levels significantly below design capacity. These systems are less efficient at reduced firing rates; controller stability also is reduced. Therefore, with uncertain future base requirements, aging equipment, and constrained budgets, a strategic direction is evolving to selectively refurbish boilers that meet minimum mechanical standards. The refurbishing of boilers will include installation of contemporary control systems.

A reliable control system is essential for maintaining safe and efficient operation of a central heating plant. Because of the rapid advance in computer and electronic technologies in recent years accompanied by substantial reduction in manufacturing costs, retrofitting outdated control systems with state-of-the-art hardware and software could be cost effective. Automatic controls for boilers and other processes in the DOD facilities generally are based on proportional integral derivative (PID) controllers. PID controllers implemented in pneumatic, electronic, or microcomputer software can be somewhat difficult to set up and may not produce stable results over a wide range of operating conditions. Adaptive controller technologies have begun to address these deficiencies. In cooperation with the University of Illinois (UI), the U.S. Army Construction Engineering Research Laboratories (USACERL) has developed and completed initial tests of a prototype adaptive controller. This general predictive controller (GPC) was applied for short-term tests on a gas-fired boiler at the UI Abbott Power Plant. Results of these tests are summarized in this report and are described more fully in Lin et al. (June 1993).

Objectives

The objectives of this study were to conduct a market survey on adaptive boiler controllers and to determine the market niche for the USACERL/UI system based on its competitiveness in terms of performance and cost.

Approach

After a preliminary search of control system vendors, eight well-known firms that manufacture adaptive boiler controllers were selected for a market survey. The survey was conducted by sending the selected vendors requests for proposals for current equipment offerings and costs for adaptive controls.

The performance of the GPC was appraised based on a comparison with the PID controller. Initial test data were collected from a boiler at the UI equipped with the PID controller. The GPC then was installed on the same boiler for testing of the GPC system under conditions similar to those for the PID controller.

The cost of the USACERL/UI GPC system was compared to the cost estimates of the vendor-supplied system to determine if the GPC was cost competitive.

Typical boiler control requirements are summarized and candidate applications for adaptive controller technology are identified in Chapter 2. The GPC concepts, equipment implementation, test results, costs, and potential benefits are described in Chapter 3. Traditional and adaptive boiler control technologies, the system selection factors, and the total implementation costs quoted by vendors are given in Chapter 4. Conclusions and recommendations for the development of the prototype system are provided in Chapter 5.

Scope

The primary focus of this work is for control system retrofits to existing gas/oil fired units in DOD facilities. Because of funding constraints and the nature of this newly evolving technology, no detailed performance comparison among all the competing products can be made at this time. The analysis and recommendations provided in this report are from the perspective of a control systems consulting engineer.

Mode of Technology Transfer

The information in this report should be disseminated in the Public Works Technical Bulletin. It is recommended that the survey results be presented at the national meeting of the American Society of Mechanical Engineers and the Electrical and Mechanical Engineering Conference sponsored by the Office of the Chief of Engineers. Support from the base utility engineers and the control system vendors is needed to form a partnership for long-term demonstration of the prototype system and the ultimate transfer of the technology to be utilized in the Army boiler plants.

2 Typical Plant Requirements

Installed U.S. Army Boilers

Installed U.S. Army boilers include units throughout the world that service steam and high temperature hot water heating loads. The distribution of U.S. Army boiler age is shown in Figure 1; the average boiler age is about 26 years.

Installed U.S. Army boilers range from small to large in size (Figure 2), with the majority, 64 percent, relatively small packaged units. These are normally single burner gas, oil, or gas/oil fired units using jack shaft controllers. The remaining units are typically over 15 million British thermal units per hour (MBtu/hr). The vast majority of these larger units are gas and/or oil fired; only 8 percent are capable of firing coal.

The larger units offer the greatest economic opportunity for control systems upgrade. Typically these units are mechanically configured to accept multiloop controls as opposed to jack shaft control. They can be subjected to a greater operating range turn-down for varying load conditions. Higher capacity units with larger attendant fuel costs offer greater opportunities for economic return because control system costs are primarily impacted by control strategy selection (sensors, valves, dampers, local and remote controls, etc.) rather than by boiler capacity.

Operating staff expertise and availability also must be considered. Operating staff sizes and experience are declining. Operators often lack experience and expertise to make the overall operating performance judgments and the minor optimization adjustments traditionally performed by operators. Sources of operating problems can be difficult to pinpoint because of the highly interrelated nature of boiler systems. Constraints on operating performance are growing in terms of tighter economic operation (i.e., sliding temperature or pressure controls). Environmental constraints also are increasing. Therefore, more robust controllers are needed to support flexible operating strategies, adapt to changing boiler or fuel conditions, and pinpoint the sources of operating problems before they impact unit availability and performance.

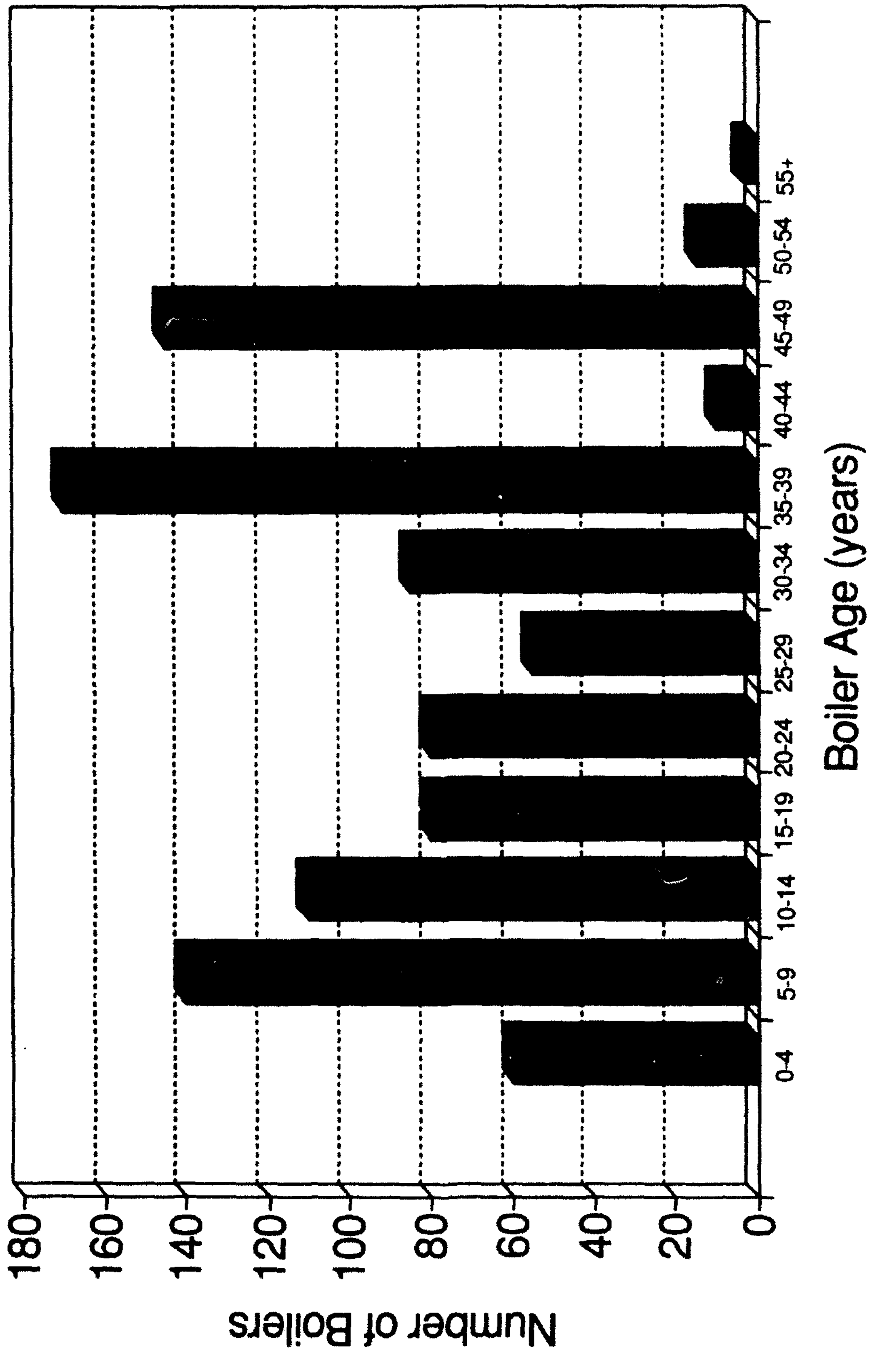

Figure 1. U.S. Army boiler age distribution.

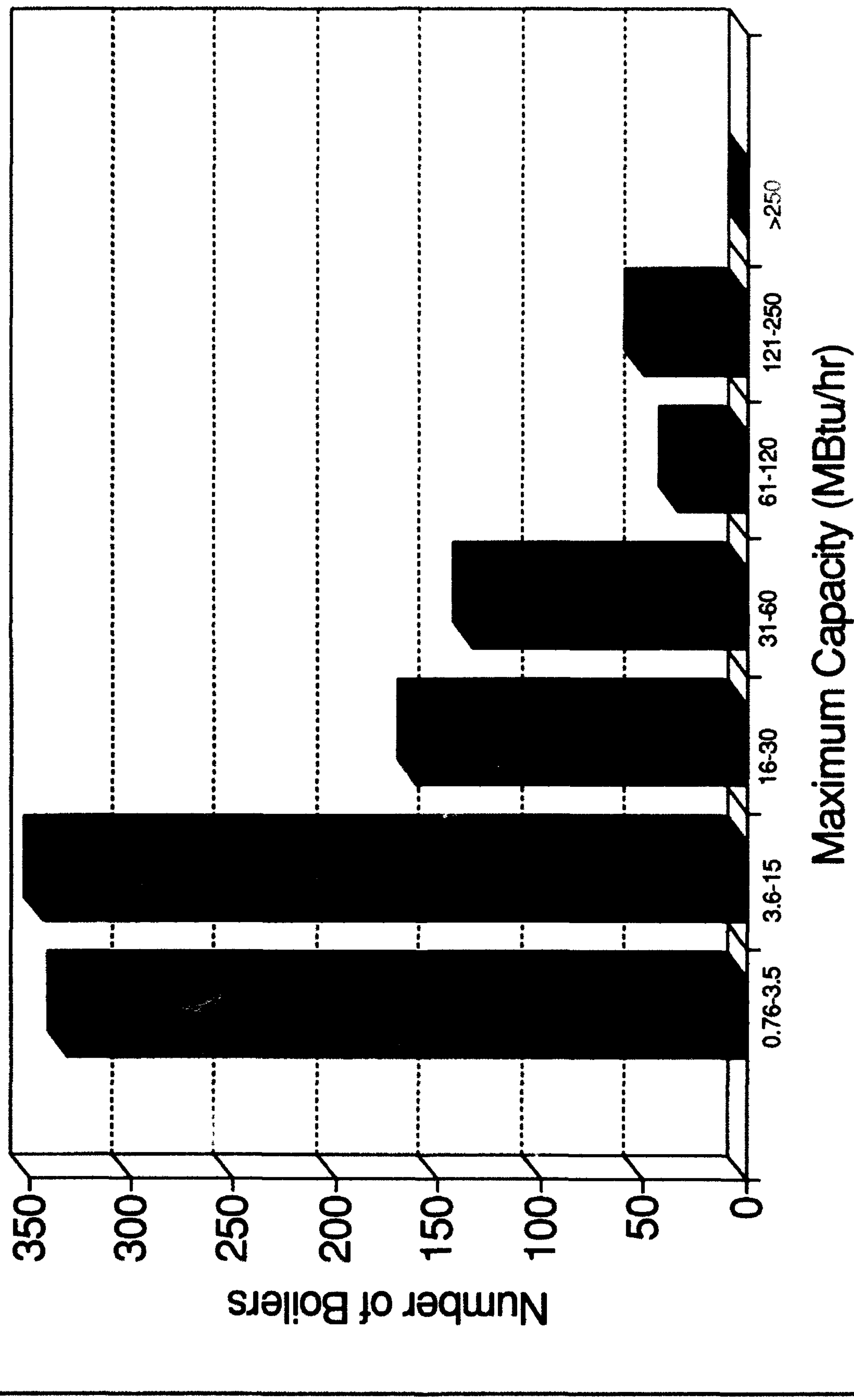

Figure 2. U.S. Army boiler size distribution.

Typical Control Systems Upgrade Design Criteria

Mechanical integrity of the boiler is an essential prerequisite for improved boiler economics and control versatility. Good controls cannot make a poor boiler operate well. However, poor or inadequate controls can significantly reduce operating economics, reliability, and safety.

Process transmitters, valves, and dampers also are critical prerequisites for improved boiler control. Transmitters are the "eyes and ears" of the control system. The best control strategy will suffer to the extent that process inputs do not reflect reality. The quality of the process signal is impaired by transmitter characteristics, range ability, mounting location, and maintenance. Dampers and valves alter process conditions based on controller inputs and strategies. They must have mechanical integrity and be appropriately sized for the process conditions.

Appropriate combustion control solutions must fit a larger overall control systems strategy. Boiler controls typically include many of the following subsystems:

- combustion controls,
- drum level—often considered as a part of combustion controls,
- burner management—the flame safety interlock logic normally provided to comply with applicable National Fire Protection Association 85 series codes,
- environmental control such as for a baghouse or precipitator and regulatory monitoring,
- fuel handling and delivery—sequential or interlocked controls and process monitors for levels, flow rates, pressures, etc.,
- ash handling,
- water treatment,
- feedwater,
- load monitoring.

The magnitude of this integration effort is increased by the tendency for equipment manufacturers to supply "packaged" control systems for the various subsystems furnished for a unit. The advent of packaged control systems integration has given rise to the centralized supervisory control and data acquisition (SCADA) function. SCADA includes the monitoring, control, historical logging, and reporting of various process and equipment conditions. The SCADA function often is implemented on a personal computer networked to the various "packaged controls." A typical boiler plant conceptual control system is shown in Figure 3.

Each of the control subsystems is important. All but combustion controls and drum level are easily implemented in traditional sequential logic or simple PID control loops. Combustion controls differ in that they are characterized by multivariate control loops involving interaction between several input variables such as steam pressure or flow, air flow, fuel flow, and furnace pressure and combustion quality (excess oxygen, nitrous oxides, carbon monoxide, etc.). Relationships between these variables are nonlinear. No one set of PID tuning parameters works well over a wide range of boiler firing rates. Therefore, control system performance is exacerbated by the part load or cyclic operation typically found today. This is the principal focus for adaptive controllers such as the GPC.

The control panel or operator interface is the point where all the controls come together. Traditionally, a panelboard is provided near the boiler with indicators, controllers, status lights, switches, recorders, and alarms. The advent of distributed control systems (DCS) technology in the 1970's and its "down scaling" to personal computer (PC)-based control software in the late 1980's offers significant opportunity to economically replace (or augment) panelboards with PC-based supervisory control and data acquisition (PC SCADA) systems with the following features:

- interactive graphic displays that can be configured for specific modes of operation (start up, single unit, multi-unit overview, alarm summary, reports, etc.);
- graphic alarm monitor to display alarm status;
- historical archive data files and trend graphs to be saved for review;
- diagnostics concerning control systems equipment, mechanical equipment, and the combustion process;
- operating reports generated automatically for evaluation;
- remote access for expert monitoring or data acquisition.

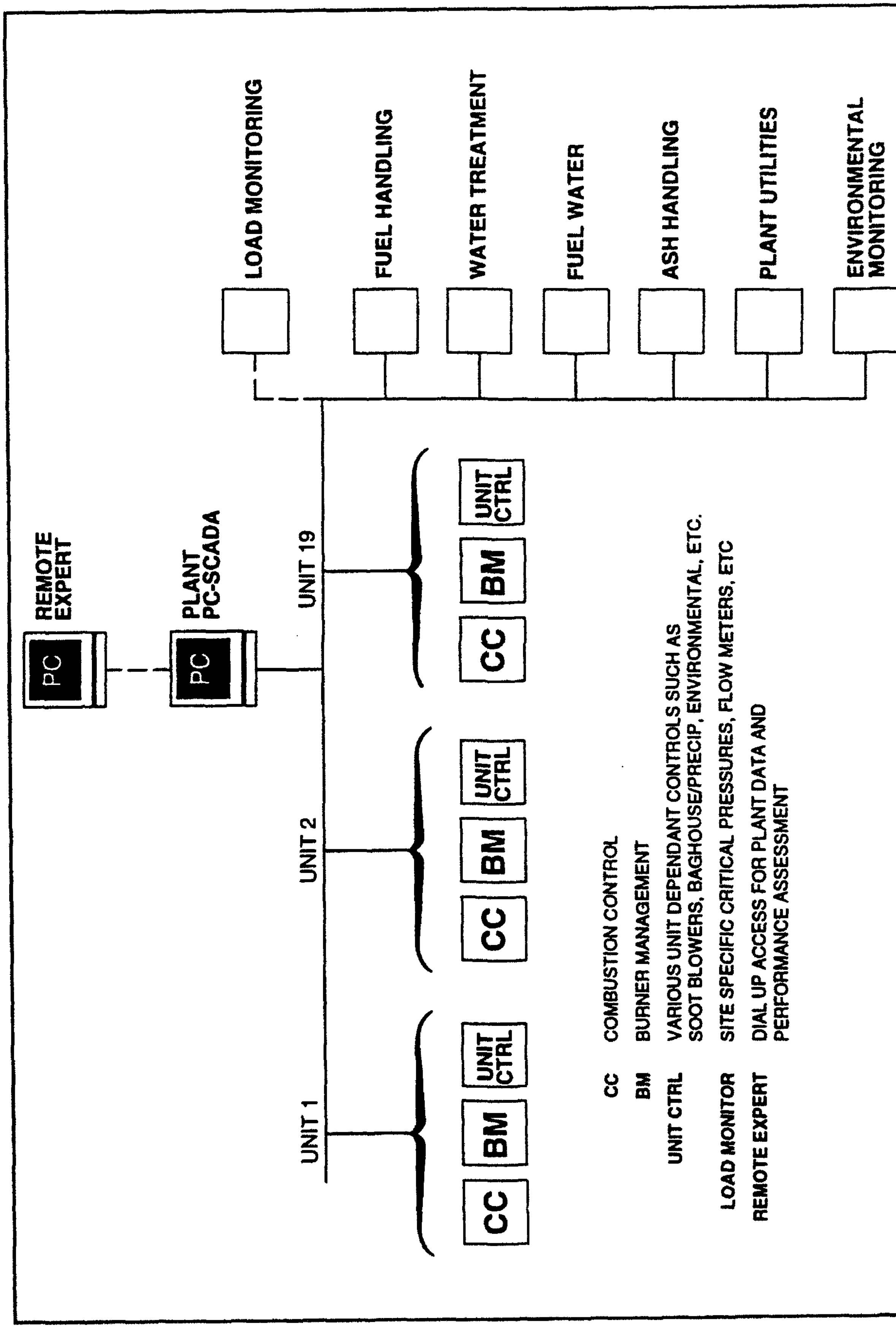

Figure 3. Conceptual plant control system.

3 The GPC Controller

GPC Background

The GPC algorithm is based on the GPC model developed by D. W. Clarke of Oxford University (Clarke et al. 1987). The GPC model is used in conjunction with a recursive least squares (RLS) identification algorithm that also incorporates parameter constituents, covariance resetting, and supervisory (or expert) logic to handle identifier start-up, shutdown, and excitation. The control system is structured as shown in Figure 4.

The regulator/tracker block is an algorithm that computes a control signal on the basis of a feedback signal (feedback sensor output); a reference input (preplanned set point or time varying signal, or a priori unknown input signal); and a feedforward signal (feedforward sensor output). The control design block is conceptual. It signifies an online regulator/tracker reparameterization that is taking place at every sampling period on the basis of current plant parameters computed by parameter estimator, and an off-line regulator/tracker design using an underlying controller synthesis method

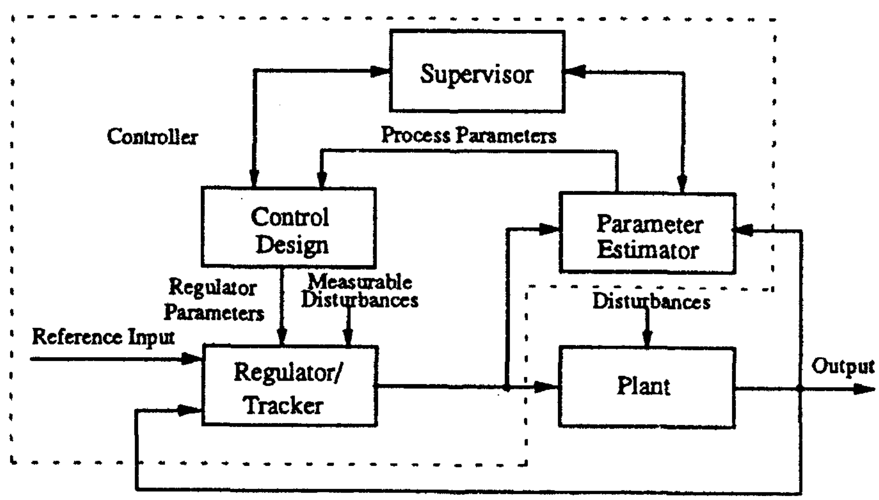

Figure 4. Basic GPC structure.

(such as GPC) and setting controller features (such as regulator structure, prediction and control horizons, and rate limits on control signal). However, if hardware permits, regulator/tracker redesign can be performed in real time in a closed loop to allow the online change of controller feature. The parameter estimator block is an algorithm (e.g., RLS algorithm) that, within a prespecified model structure, computes online the parameters of the model to approximate plant input/output behavior on the basis of output measurements (feedback output sensor signal) and plant input (control signal). The supervisor block signifies the real-time diagnostics of the self-tuner, such as identifier conditioning depending on the richness of online information in the input/output signals; nonreal-time operator/designer interface with identifier for the purposes of changing identification procedure and/or identifier structure; nonreal-time operator/designer interface with control design block for the purpose of resetting "tuning knobs" in control design procedure and the regulator/tracker structure. If hardware permits, the last two tasks can be performed in real-time, resulting in the so-called intelligent self-tuner.

The GPC uses default values for those parameters of the controller that otherwise must be chosen at commissioning time. The algorithm uses a discrete-time transfer function to predict future boiler process values and to determine the control action. At each sampling instant, a new value for the output control signal is calculated that minimizes the sum of the squares of the predicted control errors over a prediction horizon, assuming no further changes are to be made to the controller output. The GPC controller can accommodate and adapt for variable process gain, dead-time variations, parameter estimates, and unstable events. It also permits the direct inclusion of constraints on the control signal, such as rate limits on the actuator response (Bitmead, Gevers, and Wertz 1990).

Test results showed that the USACERL/UI GPC boiler control system exhibited robust performance. This means that the controller can effectively track the process output to a reference input, with disturbance rejection, and preserve such performance under changing process and equipment characteristics over time.

The GPC was implemented on a µMAC 6000* using C programming language. The supervisory function was implemented via THE FIX** software package on an IBM compatible personal computer. Initial boiler simulation was performed on an HP 9000 model 825 minicomputer. Control outputs were buffered from the test boiler with

* Manufactured by Analog Devices, Inc., One Technology Way, P.O. Box 9106, Norwood, MA 02060, tel. 617-329-6666. Note that µMAC controllers currently are sold by Azonix Corp., 900 Middlesex Turnpike, Building 6, Billerica, MA 01821, tel. 1-800-365-1663 (toll free).

** Produced by Intellution, Inc., 315 Norwood Park South, Norwood, MA 02060, tel. 617-769-8878.

LOOPMATE[***] manual auto stations to permit local manual control and to maintain last value in the event of a controller failure.

The process model was developed from test data taken on the Abbott Power Plant Boiler No. 2 at the UI. Both closed loop PID and open loop (local manual on the PID controller) data were collected. Models were developed, and initial parameters were selected using lab simulation. The resulting model was installed on the boiler, and tests were conducted July 10 through July 12, 1991.

Results of USACERL/UI GPC Developments

GPC test results were compiled by UI researchers (Miller et al., April 1992). The test results are shown in Figures 5 and 6. Figure 5 shows the drum pressure and set point with GPC. Though the set points were varied over a wide range [from 347 to 323 pounds per square inch (psi) in less than 1000 seconds], the loop output tracked the set point closely. This is extremely difficult for the conventional PID control. Tighter drum pressure control can improve upset recovery and operational safety. Figure 6 shows the test results for exhaust oxygen and set point with the GPC. It is clear that the performance of this control loop is extremely good.

Direct comparison of GPC and PID controller performance proved difficult because the boiler had no sensor for set-point measurement when the conventional pneumatic PID controllers were in use. It was impossible to match precisely the operating conditions between periods of GPC and PID controller operation. However, a limited comparison could be made. Figure 7 shows the comparison of the step response of PID and GPC control for the excess oxygen loop. It was clear that, with the GPC, the step response of the excess oxygen is much tighter (within 0.2 percent oxygen) than with the PID control (within 0.5 percent oxygen). The GPC algorithm provided excellent control of combustion. This, potentially, has a large immediate payback. Excess oxygen trim control is the key to economic operation. Figures 8 and 9 provide the limited comparison of the test results of drum water level loop with GPC and PID control.

In general, the test results were rated good for an initial attempt. Results for drum pressure and excess oxygen loops are encouraging. Minor problems encountered during the test were later resolved with minor corrections to the controller sampling frequency.

[*] Manufactured by Control Technology, Inc., 5734 Middlebrook Pike, Knoxville, TN 37921, tel. 615-584-0440.

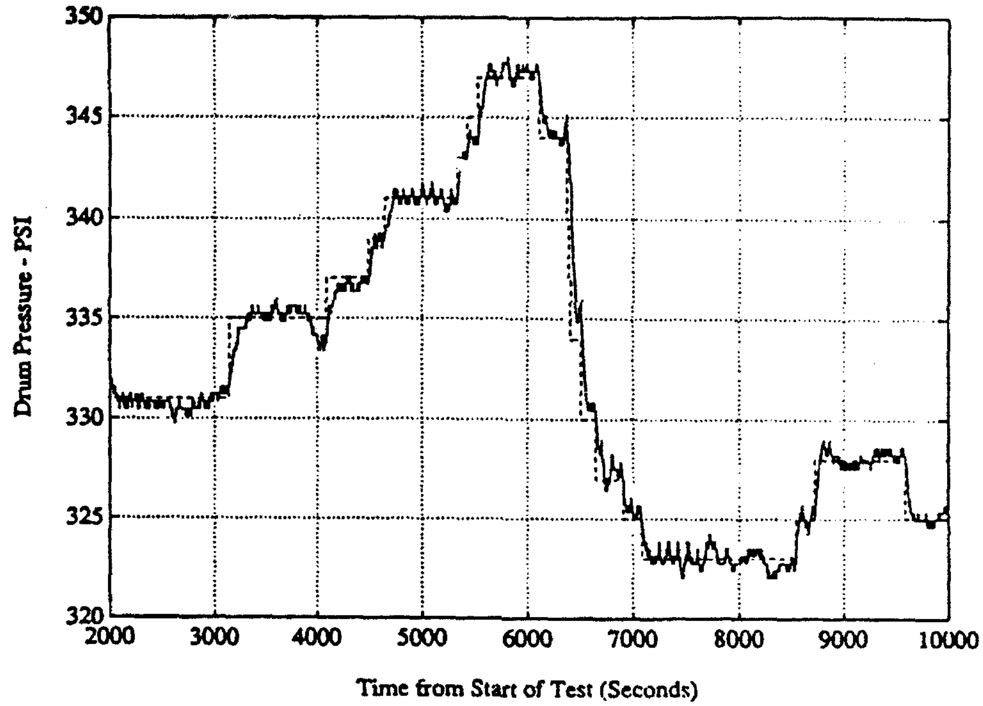

Figure 5. Drum pressure set point with GPC.

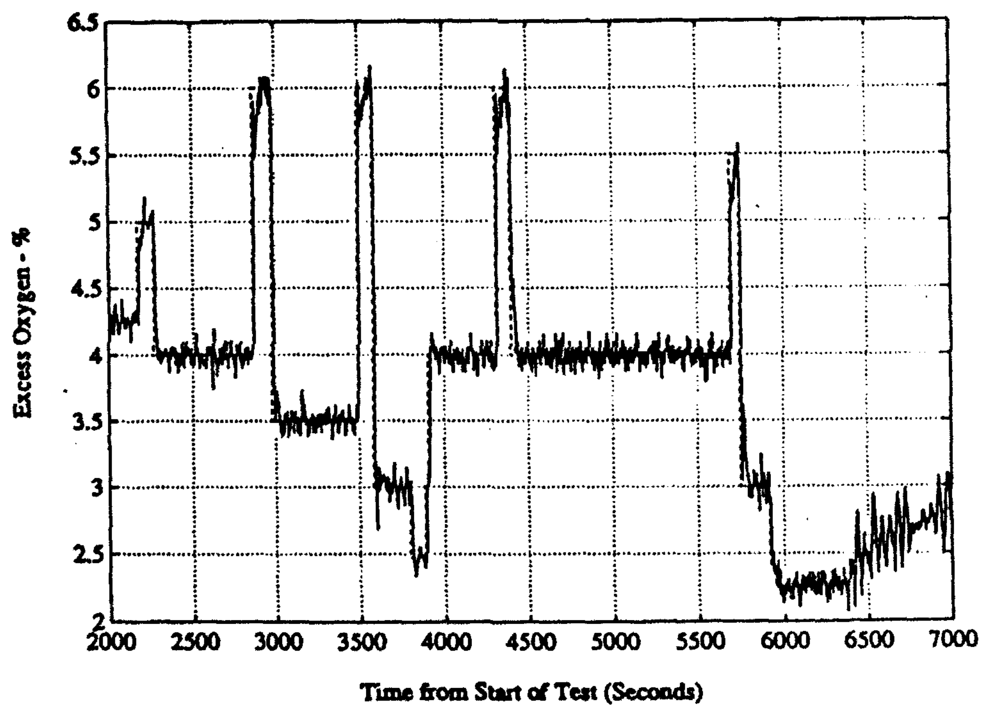

Figure 6. Exhaust oxygen and set point with GPC.

Additional feasibility assessments were provided for application of GPC to coal-fired units (Warner, February 1992). Models apparently can be applied universally to boilers of a similar type, in the same way that typical PID combustion control strategies currently are applied to various types of units. Potentially greater benefits than those obtainable for gas/oil fired units may be obtained by applying GPC strategies to coal. The larger variations in fuel feed rate, British thermal unit content, fuel feed lag, and stored energy component all suggest opportunities for improved, adaptive control strategies. The increased complexity of proper air and fuel distribution, slagging, and equipment and environmental constraints suggest additional opportunities for improved operating diagnostics and control system robustness.

Traditional PID loops are limited to a single process variable and set point. More complex cascaded or feed forward multi-PID loop control strategies are required to implement combustion controls. However, these multiloop strategies are not particularly well suited for coping with process lags and variable process gains over the operating range. GPC's appear to have significant potential for adaptive, multivariate applications.

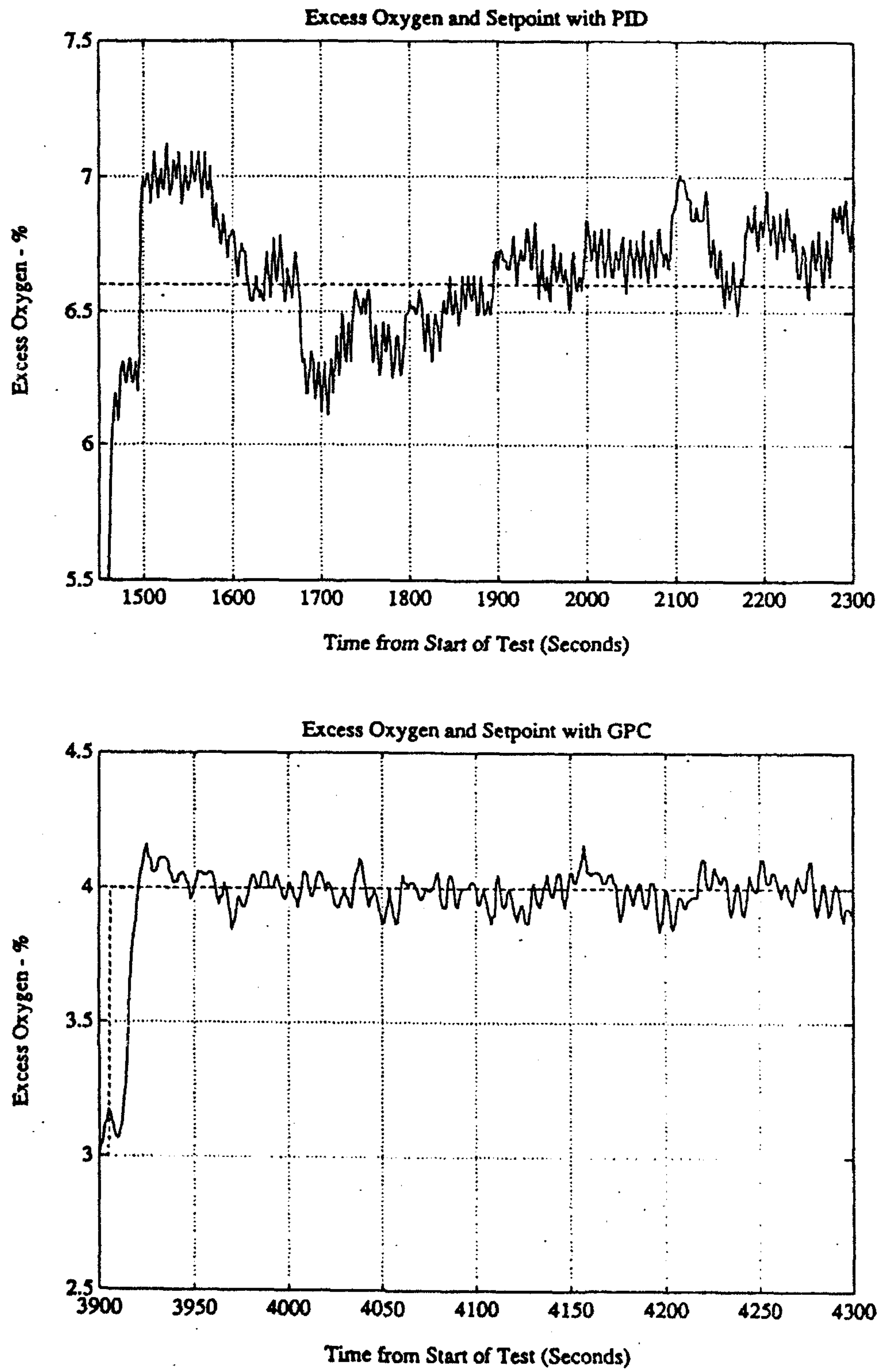

Figure 7. Comparison of the step response of PID and GPC for the excess oxygen loop.

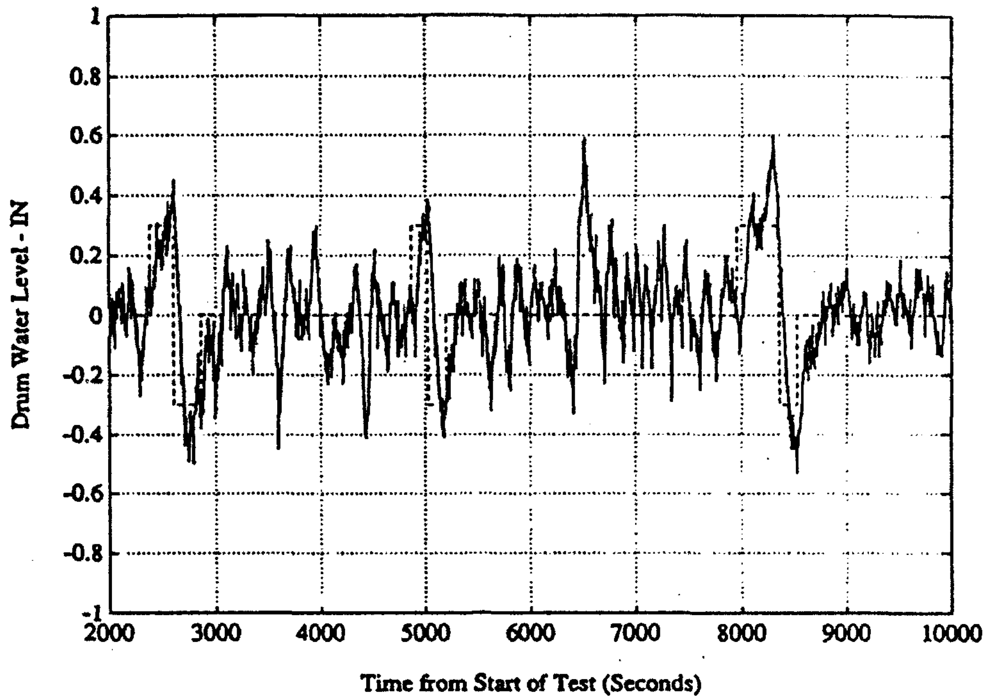

Figure 8. Drum water level and set point with GPC.

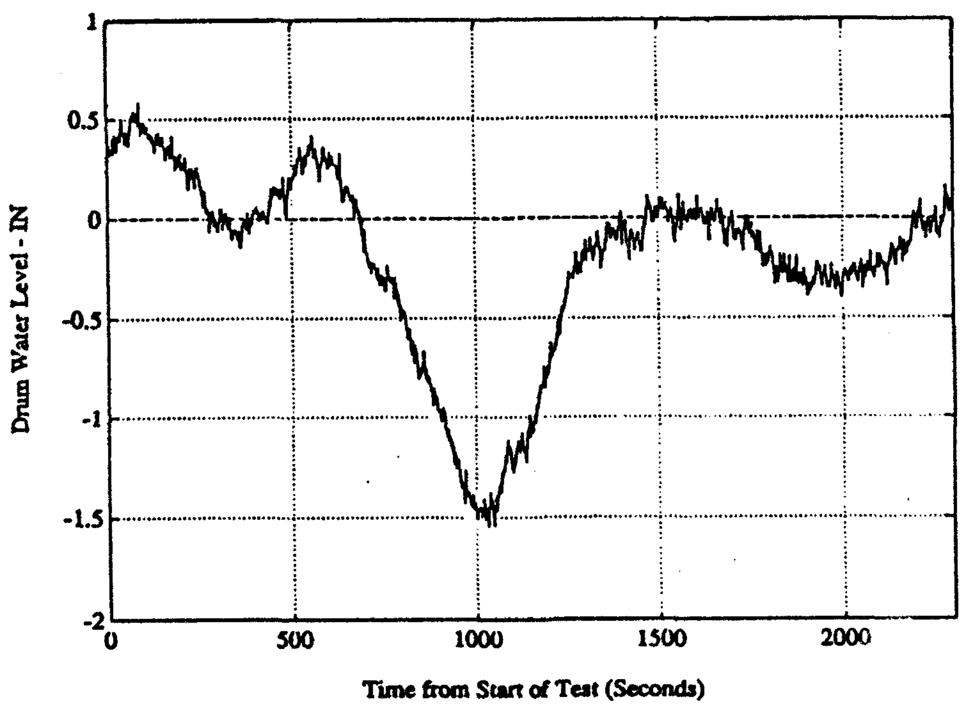

Figure 9. Drum water level and set point with PID control.

4 Competitive Control Systems

Traditional Control Systems

The purpose of any controller is to ensure robust performance. This means that the controller must track the set point by adjusting its output while rejecting disturbances in the input process variable signal, under varying plant characteristics throughout the range of the controller.

Process controllers traditionally have been implemented as PID controllers incorporating proportional, integral, and derivative functions contributing to the PID controller output. Each component has a constant parameter assigned to it (K_p, K_i, or K_d). The proportional term is based on the deviation between the controller set point and the process variable, multiplied by the proportional constant, K_p. The integral term is accumulated over time and represents the historical sum of the weighted (k_i) deviations between process variable and set point. The derivative constant, K_d, is applied to the rate of change for the process input (i.e., error minus previous error). Various terms of the PID controller can be updated at different time intervals.

A number of factors have to be considered in developing an effective tuning procedure for PID controllers. These include different process characteristics, process nonlinearities, and process uncertainties. Different signal formats, PID algorithms, and the need to accommodate noisy signals also impact controller tuning. Although the PID controller uses a linear control algorithm, it can work well on nonlinear processes if the nonlinearity is not too strong or the operating range is sufficiently restricted. Several boiler control loops are decidedly nonlinear, particularly regarding excess oxygen. Process uncertainty is an important factor in loop tuning. An aggressively tuned PID may perform well under normal conditions but become oscillatory or even unstable when the process dynamics change. Dynamics may change as a result of change in operating conditions (i.e., a change in set point or in process feed rate). Process dynamics also may change because of varying conditions over time such as gradual fouling of heat transfer surfaces. PID algorithms are implemented differently by various hardware and software manufacturers and require different tuning techniques. Noise in the process variable often creates a high frequency random signal superimposed on the process variable that can adversely

affect PID controller stability. Noise is typically induced by measurement elements or the process itself.

PID controllers have been implemented using numerous technologies. Most boilers installed prior to 1975 used pneumatic controller technology. This represents a sizeable portion of the U.S. Army boilers. Boilers installed in the 1970's primarily used electronic controllers for PID functions. Large boiler complexes built in the 1970's and 1980's use DCS technologies that are elaborate microprocessor networks with the PID controllers installed in software or hardware. The DCS controller installations have given way to distributed microcontroller technologies in the late 1980's and early 1990's that also install the PID functions in software or hardware. The advent of software-installed PID functions has increased PID versatility, range, and flexibility to adapting tuning parameters by selecting preprogrammed tuning constants under varying circumstances.

Adaptive Controllers

Model-based predictive controllers are similar to our own learning experience. Four activities are involved: training, targeting, action, and comparison.

The analogy of learning to drive a car helps illustrate these points. Training is done by trial and error. An individual develops expertise by learning that an action on the gas pedal induces a certain acceleration, and so forth. Targeting relates to identifying where an individual wants to go and anticipating what is ahead. Action relates to behavior. Because the future behavior is defined by the target, optimum solutions based on historical performance can be applied. Expected and actual values are compared. If a deviation does not reappear for a given circumstance, the deviation can be attributed to unique conditions. If a condition persists, slight adjustments are needed to compensate.

The difference between model-based control and predictive control is that the model-based control techniques estimate dead time in the feed forward path of a control system, but they do not predict more than pure delay time. Predictive control makes a decision in real time at every sampling period according to future time targets. Incremental predictions are expressed in terms of a reference trajectory that specifies the desired closed loop behavior in terms of a response time. In practice, a tentative string of process variables is examined to achieve the best possible match between the desired reference trajectory and the predicted output. If this procedure (or scenario) were not predictive, the methodology would loose its ability to handle constraints and would provide no optimal control, feed forward action, immunity to noise, etc. and

would exhibit a degraded robustness. In this simplest case, model-based controllers are reduced to linear quadratic controllers (PID) (Richalet, August 1992).

Several adaptive controller technologies currently are under development and in limited use (Verduin, July 1992; Kosko 1991), including fuzzy logic, neural networks, GPC, and state logic. At this time there is no clear answer about which technology is superior. Indeed, all these technologies may offer advantages under various circumstances and applications.

The concept of fuzzy logic was first proposed by Professor Lotfi Zadeh of the University of California at Berkeley more than 25 years ago (Zadeh 1968). A fuzzy set does not have a crisp boundary. It can be represented by a membership function $\mu_A(x)$ that represents the grade of membership of the element x in the fuzzy set A. If $\mu_A(x)=1$ for some value x, then this value is definitely a member (element) of the set A. Similarly, $\mu_A(x)=0$ implies that the particular x is definitely outside of the set A. A value within the range $0 < \mu_A(x) < 1$ means that the membership of x in A is vaguely defined. In this manner a vague or inexact quantity can be represented by a membership function with an associated fuzzy set. Such a membership function is a possibility function, which indicates the degree of possibility that a particular item is a member of the set A.

A fuzzy controller is conceptually rule based and consists of a group of fuzzy control rules obtained from a control expert's experience and knowledge. The starting point of a conventional fuzzy control is the development of a rule base using linguistic descriptions of control protocols, say, of a human expert. This step is analogous to the development of a hard control algorithm and the identification of parameter values for the algorithm, in a conventional control approach. During the control action, process measurements are matched with rules in the rule base, using the compositional rule of inference, to generate fuzzy control inferences. This inference procedure is clearly analogous to feedback control in a hard control scheme.

The ability to handle degrees of truth and multivariable membership, instead of black-and-white alternatives, is what makes the fuzzy method different. Yet fuzzy logic makes sense out of vagueness through a gradation of numerical values (between 0 and 1) assigned to its membership functions. After defuzzifying the fuzzy control inferences, numeric values are used to derive a crisp solution to a problem.

Fuzzy logic offers several benefits to controls. It does not rely on complex mathematical equations or extensive look-up tables and is more tolerant of noisy signals than traditional control methods. Equations may become impractical in some instances: in nonlinear or dynamically complex systems or in ones with unusual input/output

combinations. Instead, the fuzzy approach uses intuitive human expertise to help solve the problem at hand.

Today, manufacturers of DCS, programmable controllers, and microcontrollers (MCU) are incorporating fuzzy logic into their products and market strategies. At the same time, growing numbers of software companies are adding tools to make fuzzy logic easier to use and apply. For example, Motorola's Microprocessor and Memory Technologies Group (Austin, TX) planned to implement most fuzzy logic applications in software on standard microcontrollers and to develop new controller hardware specially designed to accelerate fuzzy processing. Aptronix, Inc. (San Jose, CA), developed a new software tool called fuzzy inference development environment (FIDE) that added fuzzy logic capabilities to Motorola's standard MCU. FIDE consists of four main parts. Its editor works with English-like statements to define rules, membership functions, inference methods, and difuzzyfication. A debugger traces data flow through the inference process. For simulating closed-loop systems, a composer offers a way to combine fuzzy and nonfuzzy modules. The real time code generator creates assembler code for Motorola's MCU. Currently, FIDE supports the 68HC05 and 11 microcontrollers; it will support the 68HC16 and 68300 MCU and the 5600 DSP family in the future.

A neural network is a massively parallel distributed processi g system with the potential for ever-improving performance through dynamic learning. It originated as a computer technology 40 years ago. Only now is the technology seen as a practical means of problem solving. Improvements in computer central processing unit speed and processing power have helped to make neural networks practical today. Of equal importance is an understanding that the capabilities of neural networks can be greatly enhanced by integration with expert system, optimization, and user interfaces, including 3-D graphical plotting capabilities as complementary computer technologies.

In neural networks, the basic nonlinear elements are called nodes or neurons. The nodes are nonlinear processing elements that sum incoming signals according to a predefined function. This function is called sigmoid threshold function, which is a bounded, monotonic, nondecreasing function that provides a graded nonlinear response. All nodes in a network are interconnected, and the strengths of the interconnections are called weights. The values of weights can be prescribed based on an off-line algorithm or adjusted via a learning process to improve performance. Learning is accomplished by adjusting these weights to minimize a special objective function. The most popular neural networks for real time control purposes are error back-propagation neural networks and Hopfield neural networks.

Combustion is a complex process. It is hard to model the combustion process with a simple mathematical equation. Combustion parameters, such as ambient temperature and humidity, and boiler characteristics are critical to combustion; however, they are not controllable. With the help of the neural networks, it is possible to get the correct combustion model online via the learning ability of the neural networks. Therefore, integrated with expert systems and optimization programs, neural networks will enable electric power utilities to save fuel and reduce maintenance.

One example of the neural networks on power plant applications is the functional link network combustion optimizer built on AI Ware's integrated technology platform. The proprietary neural network serves a vital role by generating a nonlinear combustion model. This model is customized for a particular boiler and is automatically updated to reflect changes in specifications, performance, and environments. The embedded expert system incorporates user inputs regarding operational constraints and preferred operating procedures, as imposed by equipment capabilities, and safety and maintenance requirements. Driven by the embedded expert system, the optimizer recommends set points that will optimize fuel usage. The optimizer helps users explore tradeoffs and opportunities in more detail, using a special function such as sensitivity analysis through the graphical user interface.

The following factors must be considered in control system selection:

- robustness - to ensure proper control under a wide variety of operating conditions,
- dynamics and accuracy - to respond correctly in varying process dynamics,
- noise immunity - to be able to filter out signal noise,
- the ability to handle constraints,
- the ability to control unstable systems,
- processing requirements - can be tailored to a specific process,
- human resources - requires no highly skilled technicians,
- ease of maintenance - service manual and spare parts available.

There is no indication that an advanced system will work better than a conventional system in all categories. In many instances the simple PID controller remains the

most effective choice. However, money making loops, such as boiler combustion controls, usually need more advanced controls than other loops and are more complex and perturbed than other loops because they are at the end of the process.

Economic Evaluation

Control system manufacturers are actively developing adaptive controller technologies, including in some instances GPC. Other research-oriented organizations such as the Electric Power Research Institute also are undertaking research and demonstration projects for adaptive controls.

A list of the control system vendors surveyed is given in Appendix A. A Request for Proposal (Appendix B) was developed to survey the vendors for current equipment offerings and costs for adaptive controls. Responses to the survey are given in Appendix C. And Appendix D gives an estimation of hardware and software prices for the USACERL/UI GPC adaptive control system.

The costs in Table 1 do not include field transmitters, valves, and damper actuators. These costs would be similar for any controller installation because similar inputs and outputs are needed for all controller installations.

Direct comparison of costs is difficult because the responses varied in content among the manufacturers (Appendix C). Quotations vary significantly with regard to inclusion of local auto/manual stations and the number of operator cathod ray tube consoles included (varied from one to four).

Table 1. Estimated system costs.

Company	Equipment	Development	Commissioning	Training	Total Cost
ABB Kent/Taylor	$ 32,000	$12,000	$ 5000	$ 6000	$ 55,000
Bailey Controls Company	$150,000	$25,000	$ 3000	$ 9000	$187,000
Fisher-Rosemount, Inc.	$129,000	$19,000	$ 7000	$ 7000	$162,000
The Foxboro Company	$232,000	$70,000	$40,000	---	$342,000
Honeywell, Inc.	$ 10,000	$10,000	$ 4000	$10,000	$ 34,000
Johnson Yokogawa Corp.	$ 51,000	$18,000	$ 6000	$ 4000	$ 79,000
Moore Products Company	$ 40,000	$ 8000	$10,000	$15,000	$73,000
Westinghouse Electric Corp.	$105,000	$36,000	$10,000	$ 4000	$155,000
USACERL/UI GPC Controller*	$ 25,000	$30,000	$10,000	$ 8000	$ 73,000

*Adapted from Appendix D.

Cost variations also may be attributed to the differences in scale of the technologies offered by the various manufacturers. Equipment implementations primarily have been influenced by customer requests and manufacturer perceptions of market opportunities. As a result, manufacturers have introduced adaptive technologies as software options on higher end, and higher cost, DCS systems for applications involving larger, more sophisticated users. As the technology matures, adaptive controllers are expected to become available in less costly single loop controllers such as the fuzzy logic controllers offered by the Johnson Yokogawa Corporation.

However, the most significant reasons for cost variation may be (1) the degree of experience available from the manufacturer in this market sector, and (2) the extent to which an adaptive boiler control project would be regarded as a development project rather than a more routine production project.

Responses from selected manufacturers were noteworthy (Appendix C). Westinghouse Electric Corp. and Johnson Yokogawa Corporation indicated development across several adaptive technologies, including self-tuning PID, fuzzy logic, and neural controllers with power plant applications in Japan. Bailey Controls Company offered a fuzzy logic installation. Other manufacturers were not specific but appear to offer self-tuning PID or rule-based approaches.

Assuming that manufacturers continue to transport adaptive technology to lower cost equipment, a GPC control system, including operator interface, apparently would need to be priced in the $70,000 to $80,000 range (1993 dollars) to be cost competitive.

According to previous USACERL/UI research (Lin et al., June 1993), a GPC-based control system could be implemented in an industrial controller capable of supporting C language algorithms. Examples of this type of equipment include GE Fanuc 9070, Modicon 984, Moore Products Mycro APACS, and others. Dual PC workstations and auto/manual stations would be required for comparison against the commercially available controller equipment described here. The controller equipment and supporting software could be procured for an estimated $35,000, or less, which would leave $35,000 to $45,000 from the competitive cost range for site specific configuration, commissioning, and training. The total cost would not be adequate to install a single demonstration development project, but it might be competitive as experience is accumulated.

The cost of a development project probably would be in the manufacturers' higher bid range, depending on the specifics and contract. There would be additional costs for field devices, construction, academic participation, and engineering fees for development of specifications. The GPC appears to be cost competitive. The significant economic

penalty for the GPC is the cost for its initial development and introduction to the market place.

5 Conclusions

A Request for Proposal was sent to eight control system vendors to survey the boiler control market for current offerings from each vendor and their cost for adaptive bciler controllers.

The results of the survey indicated that control system manufacturers are actively developing adaptive controller technologies, including self-tuning PID, fuzzy logic, and neural controllers. The GPC adaptive technology is a recent development in the industrial/utility adaptive controller market. There has not been enough work done with the various adaptive controller technologies in commercial applications to prove that an advanced system will work better than a conventional system. In many instances the simple PID controller is the most effective system. But model-based controllers, such as the GPC, are expected to outperform state-variable and rules-oriented adaptive logic methods in some situations.

The GPC can be regarded as competitive against other available, adaptive control system technologies. GPC offer several advantages over conventional PID controllers:

- GPC are configurable to optimize performance, not just stability, over the entire operating range.
- GPC are capable of handling linear and nonlinear processes. This is particularly beneficial for combustion control and drum level applications because of the nonlinear nature of these processes.
- GPC are robust; they have the ability to adjust to varying dynamic process gains, lags, and noise.
- GPC have the capability to support bounded output behavior.
- GPC have the ability to support multivariate control strategies.
- GPC are self-tuning, including the advantage that the unit does not need to be taken out of automatic or significantly perturbed to tune it.

PID controllers currently have some advantages over GPC:

- PID controller equipment is widely available from commercial sources.
- PID controller principles and methods are widely understood and applied.
- PID do not have the drawback of the GPC self-tuning feature, which needs to be further assessed in terms of redundancy or default provisions.

The cost estimates submitted by the vendors surveyed were difficult to compare because the equipment specified in their budgetary proposals varied, sometimes significantly. Some of this variation in cost can be attributed to the level at which some manufacturers currently offer adaptive technologies, frequently by individual customer requests. Also, some manufacturers may regard adaptive boiler controllers as a development project rather than a production project. The manufacturers may begin to reduce costs as adaptive systems are used more frequently. To be competitively priced, a GPC system would need to be in the $70,000 to $80,000 price range. The estimated USACERL/UI GPC system cost is approximately $73,000.

6 Recommendations

It is recommended that a demonstration project be undertaken to apply GPC techniques to an operating unit. Previous tests have been for short periods of time and have not sufficiently demonstrated the robustness of the control system and the feasibility of its support on a continuous basis.

Candidate sites for future long-term demonstration should have the following characteristics:

- A boiler that is mechanically sound or capable of being restored to a mechanically sound condition in terms of setting, breaching, burners, auxiliary pumps, fans, and electrical switchgear.
- A gas/oil fired unit in the 50 MBtu/hr or above class, with separate actuators for fuel and air. A jack-shaft controlled unit might be retrofitted with separate actuators.
- Other boiler capacity onsite so availability of the demonstration unit is not critical to the base.
- Availability of experienced operators and maintenance personnel to support initial operation.

It is recommended that the project combine the resources of academic researchers, a control systems manufacturer, and a consulting engineer. Each has a different perspective with regard to the development and implementation of a practical online demonstration project.

The project approach includes development of project specifications by the consulting engineer. Specifications would be developed with the assistance of academic researchers and targeted at control systems manufacturers. The selection of a manufacturer to be awarded the contract should be based on an evaluation of several factors, including related experience, project team qualifications, and service and support organizations to sustain the site during the warranty period. The low bid should not be the principal basis for selection. The manufacturer awarded the contract

should take the lead in integrating the technology with the assistance of the academic researchers and the consulting engineer, including participation in key meetings and tests. Results of the installation should be documented via commissioning tests and periodic operating reports during the first year of operation.

If favorable results are achieved with the initial operation of the demonstration unit, it is recommended that the technology be reapplied to three or four other units of varying types and/or characteristics. The focus of these additional installations would be to minimize changes between the various units to determine that standard models can be applied broadly to boilers of different classes, much as standard combustion control and drum level multi-loop strategies have evolved for PID controllers. The additional demonstration units also are intended to create greater exposure and acceptance in the DOD community while addressing critical needs for upgrade of existing boiler control systems.

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Acronyms and Abbreviations

CPW	Center for Public Works
DCS	distributed control systems
DOD	Department of Defense
FIDE	fuzzy inference development environment
GPC	general predictive controller
MBtu	million British thermal units
MCU	microcontrollers
PC	personal computer
PID	proportional integral derivative
RLS	recursive least squares
SCADA	supervisory control and data acquisition
UI	University of Illinois
USACERL	U.S. Army Construction Engineering Research Laboratories

Appendix A: Control System Vendors Surveyed

A Request for Proposal (Appendix B) was sent to the following control systems vendors to solicit information and costs for adaptive controller technologies.

Control System Vendor	**Contact**
Bailey Controls Company	Mr. John Johnson Bailey Controls Company Suite 2000 777 Oakmont Lane Westmont, IL 60559 Telephone: (708)323-1633 Fax: (708)323-2061
Fisher-Rosemount, Inc.	Mr. Karl Dittman Fisher-Rosemount, Inc. 865 Parkview Lombard, IL 60148-3200 Telephone: (708)495-8383 Fax: (708)495-0248
The Foxboro Company	Mr. R.E. Schwantes, Sr. The Foxboro Company 1901 South Busse Road Mt. Prospect, IL 60056 Telephone: (708)640-3100 Fax: (708)596-8549
Johnson Yokogawa Corporation	Mr. J.D. Basham Johnson Yokogawa Corporation Suite #302 650 West Grand Avenue Elmhurst, IL 60126-1017 Telephone: (708)941-0009, ext 303 Fax: (708)941-0049

Moore Products Company	Mr. Stephen J. Spontak Moore Products Company 799 Roosevelt Road Building 4, Suite 313 Glen Ellyn, IL 60137 Telephone: (708)790-3550 Fax: (708)790-0170
Westinghouse Electric Corp.	Mr. D.B. Fontana Westinghouse Electric Corp. 34 Russo Place Berkeley Heights, NJ 07922 Telephone: (908)665-8440 Fax: (908)665-9115
Honeywell, Inc.	Mr. Bob Lanbein Industrial Automation Division Honeywell, Inc. 621 Rt. 83 Bensenville, IL 60106 Telephone: (708)860-3869 Fax: (708)860-3868
ABB Kent/Taylor	Mr. Lloyd Windham Stalling & Company, Inc. (ABB Kent/Taylor Distributor) 1644 Vincennes Ave. P.O. Box 10 Chicago Heights, IL 60411 Telephone: (708)756-1470 Fax: (708)756-3030

Appendix B: Request for Proposal

USACERL - TYPICAL PLANT
Plant Upgrades
10838-5

STATEMENT OF REQUIREMENT

Furnish a boiler control system using adaptive controller techniques, to meet specified requirements for two 40 MBtu class gas/oil fired boilers. The boilers will be upgraded on a "one at a time" basis with up to two years between upgrades. The boilers are presently "JACKSHAFT" type controls but will be refitted to provide individual control of gas, oil, and air. A separate drive will be provided for oxygen trim. Software configuration, commissioning, O&M manuals, and training are included in the scope of services. Field instruments, actuators, installation, and wiring are by others.

Implement combustion and drum level controls using adaptive controllers to provide capability that is functionally equivalent to the SAMA diagrams attached. The adaptive controllers may directly replace the PID loops illustrated or a multivariable adaptive controller may be used. Implement the additional Inputs and Outputs (I/O) shown in the attached I/O schedule. Provide start/stop controls for various pumps. Auxiliary loops may be implemented as either adaptive or traditional PID controllers. Provide alarms for high and low analog inputs, selected discrete failure conditions, and control system diagnostics.

Adaptive controller technologies may include neural logic, fuzzy logic, GPC (based on the generalized predictive model), or other similar technique. Please include alternate adaptive control techniques if available. While proven experience will be evaluated, recent emerging offerings are of interest since we are at a stage where we are evaluating feasibility of alternatives, rather than at a point where the quoted systems will be installed.

A conceptual network diagram is attached. The network can be implemented using either "single loop" controllers or "multiloop" controllers. At a minimum provide one Operator Station and one boiler control node with local M/A stations. The network shall be expandable to add multiple independent boiler controllers linked to one or more Operator Stations in the future. Status of the boiler and plant shall be displayed on two sets of redundant graphic screens with additional screens to support tuning, process and control equipment diagnostics, alarms, and trends for selected analog values. Provide remote access for access for performance data from a remote computer (remote computer furnished by others).

USACERL
TYPICAL PLANT
Plant Upgrades
10838-5

ADAPTIVE BOILER CONTROLS BUDGETARY PROPOSAL

Manufacture:______________________ Representative:______________

Technical Contact:_________________

Telephone:______________________ FAX:______________________

Equipment Name:____
Network diagram sketch including key modules.

Adaptive Controller technology used:_____________________________
Attach information describing adaptive principles used and methods to build the control model. Please include expected improvements in process control over traditional PID.

Approximate number of installations.______________________________

Recommended training requirements (duration) required to orient operations and maintenance staff to support and diagnose routine problems.________
____

Is the controller hardware proposed capable of supporting user developed "C" language applications?____

Budgetary Costs:

Equipment:	$____________
Development:	$____________
Commissioning:	$____________
Training:	$____________

Please, attach hardware and software catalog sheets.

Submitted By: ________________________

Date: ______________________________

USACERL
Boiler Control Upgrades
Typical I/O Schedule

I/O Tag	Service	I/O Type	AI	AO	DI	DO
HSE	Boiler Feed Pump No. 1 E-Stop	DI	0	0	1	0
HSS	Boiler Feed Pump No. 1 Start	DO	0	0	0	1
HST	Boiler Feed Pump No. 1 Stop	DO	0	0	0	1
XS	Boiler Feed Pump No. 1 Run Status	DI	0	0	1	0
ZS	Boiler Feed Pump No. 1 Auto Status	DI	0	0	1	0
HSE	Boiler Feed Pump No. 2 E-Stop	DI	0	0	1	0
HSS	Boiler Feed Pump No. 2 Start	DO	0	0	0	1
HST	Boiler Feed Pump No. 2 Stop	DO	0	0	0	1
XS	Boiler Feed Pump No. 2 Run Status	DI	0	0	1	0
ZS	Boiler Feed Pump No. 2 Auto Status	DI	0	0	1	0
HSE	Fuel Oil Pump No. 1 E-Stop	DI	0	0	1	0
HSS	Fuel Oil Pump No. 1 Start	DO	0	0	0	1
HST	Fuel Oil Pump No. 1 Stop	DO	0	0	0	1
XS	Fuel Oil Pump No. 1 Run Status	DI	0	0	1	0
ZS	Fuel Oil Pump No. 1 Auto Status	DI	0	0	1	0
HSE	Fuel Oil Pump No. 2 E-Stop	DI	0	0	1	0
HSS	Fuel Oil Pump No. 2 Start	DO	0	0	0	1
HST	Fuel Oil Pump No. 2 Stop	DO	0	0	0	1
XS	Fuel Oil Pump No. 2 Run Status	DI	0	0	1	0
ZS	Fuel Oil Pump No. 2 Auto Status	DI	0	0	1	0
PAHH	Steam Drum High Pressure Trip	DI	0	0	1	0
PI	Steam Drum Pressure	AI	1	0	0	0
FI	Steam Flow	AI	1	0	0	0
FI	Steam Drum Level Control	AI	1	0	0	0
LAHH	Steam Drum High Level Trip	DI	0	0	1	0
LV	Steam Drum Level Control	AO	0	1	0	0
LALL	Steam Drum Low Level Trip	DI	0	0	1	0
LI	Steam Drum Level	AI	1	0	0	0
LALL	Steam Drum Aux. Low Level Trip	DI	0	0	1	0
LI	Steam Drum Level	AI	1	0	0	0

I/O Tag	Service	I/O Type	AI	AO	DI	DO
TI	Feedwater Economizer Inlet Temperature	AI	1	0	0	0
TI	Feedwater Economizer Exit Temperature	AI	1	0	0	0
PAHH	Natural Gas High Pressure Trip	DI	0	0	1	0
PALL	Natural Gas Low Pressure Trip	DI	0	0	1	0
PI	Natural Gas Pressure	AI	1	0	0	0
PI	Natural Gas Header Pressure	AI	1	0	0	0
FI	Natural Gas Flow	AI	1	0	0	0
FV	Natural Gas Flow Control	AO	0	1	0	0
PALL	Fuel Oil Low Pressure Trip	DI	0	0	1	0
PI	Fuel Oil Pressure	AI	1	0	0	0
FI	Fuel Oil Flow	AI	1	0	0	0
FV	Fuel Oil Flow Control	AO	0	1	0	0
TI	Fuel Oil Temperature	AI	1	0	0	0
PALL	Atomizing Media Low Pressure Trip	DI	0	0	1	0
FALL	Atomizing Media Low Flow Trip	DI	0	0	1	0
PDI	Flue Gas Flow	AI	1	0	0	0
FY	Forced Draft Fan Damper Control	AO	0	1	0	0
TI	Flue Gas Economizer Inlet Temperature	AI	1	0	0	0
TI	Flue Gas Economizer Exit Temperature	AI	1	0	0	0
AI	Flue Gas Oxygen	AI	1	0	0	0
AY	Oxygen Trim Damper Control	AO	0	1	0	0
AZ	Oxygen Trim Damp Position	AI	1	0	0	0
PALL	Compressed Air Low Pressure Trip	DI	0	0	1	0
FI	Blowdown Flow	AI	1	0	0	0
FV	Blowdown Flow Control	AO	0	1	0	0
FV	Blowdown Conductivity Flow	DO	0	0	0	1
CI	Blowdown Conductivity	AI	1	0	0	0
PALL	Furnace Low Pressure Trip	DI	0	0	1	0
XI	Forced Draft Fan Run Status	DI	0	0	1	0
XI	Flame Safeguard Modulation	DI	0	0	1	0
XI	Flame Safeguard Low Fire	DI	0	0	1	0
XI	Flame Safeguard Purge	DI	0	0	1	0
XI	Flame Safeguard Master Fuel Trip	DI	0	0	1	0

I/O Tag	Service	I/O Type	AI	AO	DI	DO
XI	Fuel Oil / Natural Gas Select	DI	0	0	1	0
XI	Dual Fuel Select	DI	0	0	1	0
	I/O POINT SUMMARY		20	6	30	9

Legend

AI - Analog Input

AO - Analog Output

DI - Digital Input

DO - Digital Output

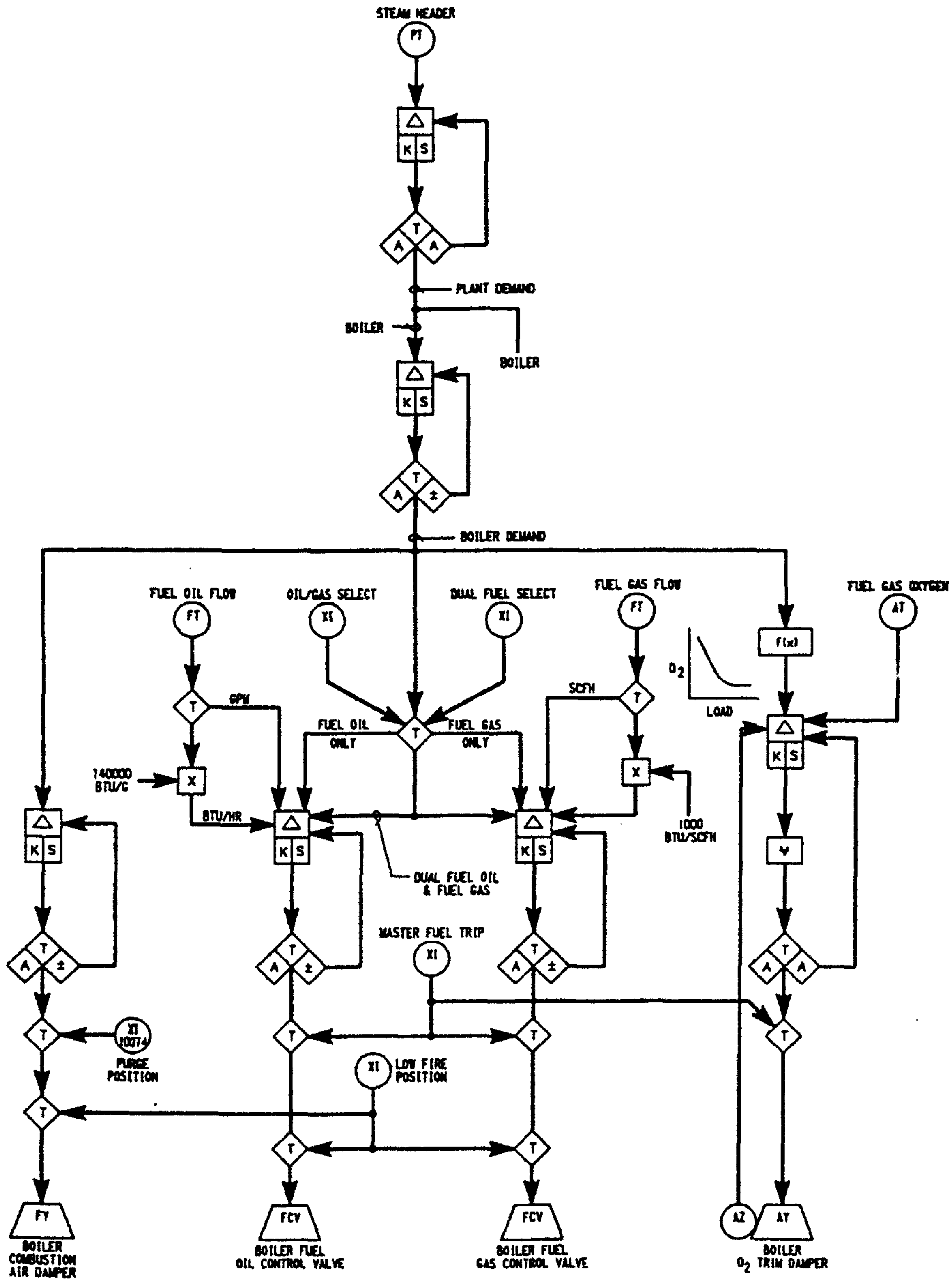

Figure B1. Typical plant SAMA (boiler combustion control).

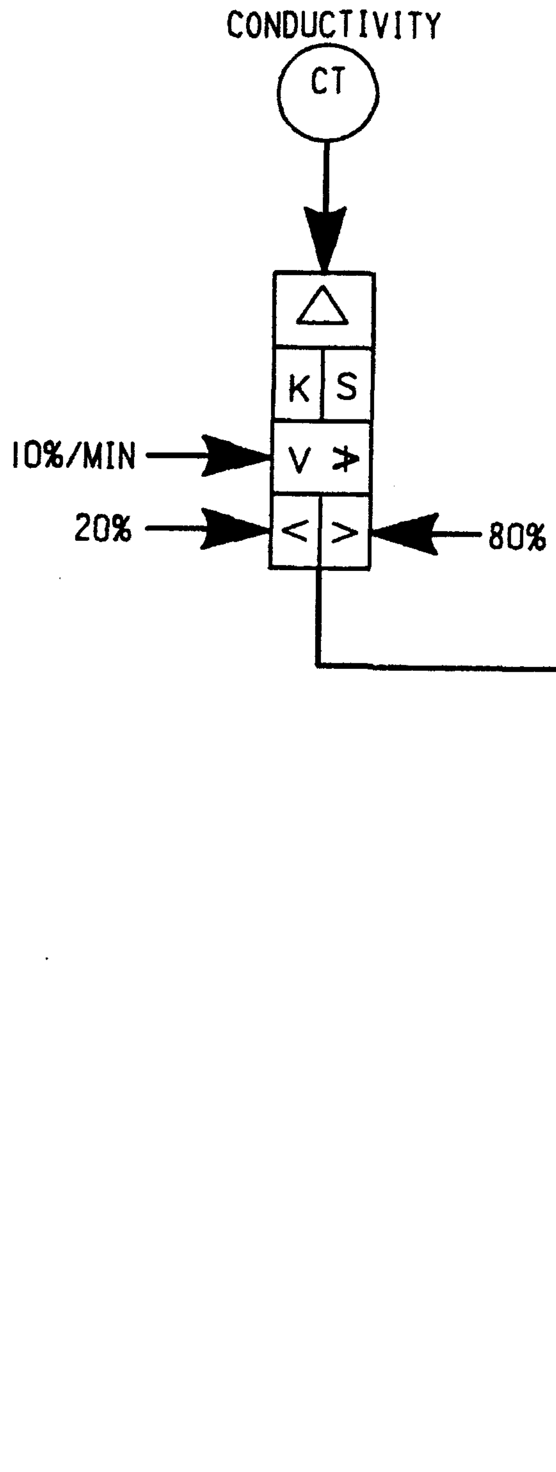

Figure B2. Typical plant SAMA (blowdown control).

Appendix C: Responses

USACERL
TYPICAL PLANT
Plant Upgrades
10838-5

ADAPTIVE BOILER CONTROLS BUDGETARY PROPOSAL

Manufacture: Johnson Yokogawa Corporation Representative: Raeco, Inc.

Technical Contact: Jack Leonard

Telephone: 404-254-0400, ext. 517 FAX: 404-251-6416

Equipment Name: MicroXL

Network diagram sketch including key modules.

Adaptive Controller technology used: Fuzzy Logic

Attach information describing adaptive principles used and methods to build the control model. Please include expected improvements in process control over traditional PID.

Approximate number of installations. >12

Recommended training requirements (duration) required to orient operations and maintenance staff to support and diagnose routine problems. 8 day course per person

Is the controller hardware proposed capable of supporting user developed "C" language applications? No

Budgetary Costs:

Equipment:	$ 50,520
Development:	$ 17,682
Commissioning:	$ 6,000
Training:	$ 4,000

Please, attach hardware and software catalog sheets.

Submitted By: [signature]

Date: January 18, 1993

USACERL
TYPICAL PLANT
Plant Upgrades
10838-5

ADAPTIVE BOILER CONTROLS BUDGETARY PROPOSAL

Manufacture: Honeywell, Inc. Representative: Honeywell, IAC Div.

Technical Contact: Bob Langbein

Telephone: 708-860-3869 FAX: 708-860-3868

Equipment Name: Series 9000, Modular Systems

Network diagram sketch including key modules.

Adaptive Controller technology used: Continuous Control Charts

Attach information describing adaptive principles used and methods to build the control model. Please include expected improvements in process control over traditional PID.

Approximate number of installations. Greater than 500

Recommended training requirements (duration) required to orient operations and maintenance staff to support and diagnose routine problems.

Series 9000 Programming and Implementation

Is the controller hardware proposed capable of supporting user developed "C" language applications? No. The controller does not support C. The PC interface does.

Budgetary Costs:

Equipment:	$ 9,653
Development:	$ 10,384
Commissioning:	$ 600/day
Training:	$ 1,380/wk/person

Please, attach hardware and software catalog sheets.

Submitted By: Bob Langbein, Senior Account Manager

Date: April 12, 1993

USACERL
TYPICAL PLANT
Plant Upgrades
10838-5

ADAPTIVE BOILER CONTROLS BUDGETARY PROPOSAL

Manufacture: The Foxboro Company Representative: R. E. Schwantes, Sr.

Technical Contact: R. E. Schwantes, Sr.

Telephone: 708-569-8549 ~~708-640-3100~~ FAX: 708-569-8549 ~~708-640-3110~~

Equipment Name: Intelligent Automation Series

Network diagram sketch including key modules.

Adaptive Controller technology used: PID with EXACT self-tuning algorithm

Attach information describing adaptive principles used and methods to build the control model. Please include expected improvements in process control over traditional PID.

Approximate number of installations. 3800

Recommended training requirements (duration) required to orient operations and maintenance staff to support and diagnose routine problems. Approximately 2 to 3 weeks depending on the digital capabilities of the people involved.

Is the controller hardware proposed capable of supporting user developed "C" language applications? Yes. Languages supported are C and FORTRAN/ FORTRAN 77.

Budgetary Costs:

Equipment:	$ 231,893
Development:	$ 70,000
Commissioning:	$ 40,066
Training:	$

Please, attach hardware and software catalog sheets.

Submitted By: [signature]

Date: 1-18-93

USACERL
TYPICAL PLANT
Plant Upgrades
10838-5

ADAPTIVE BOILER CONTROLS BUDGETARY PROPOSAL

Manufacture: Bailey Controls Co. Representative: John A. Johnson
Sr. Exe. Sales Engineer

Technical Contact: John A. Johnson

Telephone: 708-323-1633 FAX: 708-323-2061

Equipment Name: Bailey Controls INFI 90 Distributed Control System

Network diagram sketch including key modules. See attached drawing and equipment list.

Adaptive Controller technology used: Bailey EXPERT 90 configuration utilities incorporating "fuzzy" logic adaptive strategies.
Attach information describing adaptive principles used and methods to build the control model. Please include expected improvements in process control over traditional PID.

Approximate number of installations. One Thousand (1000) plus

Recommended training requirements (duration) required to orient operations and maintenance staff to support and diagnose routine problems. One (1) week

Is the controller hardware proposed capable of supporting user developed "C" language applications? Yes

Budgetary Costs:

Equipment:	$ 150,000
Development:	$ 25,000
Commissioning:	$ 2,800
Training:	$ 9,400

- Plus $1000 per man-day plus expenses for implementation of adaptive control strategies in Bailey EXPERT 90 configuration utilities by a Bailey Applications Engineer.

Please, attach hardware and software catalog sheets.

Submitted By: [signature]
Proposal Engineer

Date: January 25, 1993

USACERL
TYPICAL PLANT
Plant Upgrades
10838-5

ADAPTIVE BOILER CONTROLS BUDGETARY PROPOSAL

Manufacture: ABB Kent-Taylor Representative: Stallings & Company, Inc.

Technical Contact: Lloyd Windham

Telephone: 708-756-1470 FAX: 708-756-1470

Equipment Name: MOD CELL/MOD 30/PC-30

Network diagram sketch including key modules.

Adaptive Controller technology used: Programmable Microprocessor based

Attach information describing adaptive principles used and methods to build the control model. Please include expected improvements in process control over traditional PID.

Approximate number of installations. 75,000

Recommended training requirements (duration) required to orient operations and maintenance staff to support and diagnose routine problems. 1 week

Is the controller hardware proposed capable of supporting user developed "C" language applications? yes

Budgetary Costs:

Equipment:	$ 32-44,000
Development:	$ 12,000
Commissioning:	$ 5,000
Training:	$ 6,000

Please, attach hardware and software catalog sheets.

Submitted By: [signature]

Date: June 3, 1993

Quotation Number: LW 535

USACERL
TYPICAL PLANT
Plant Upgrades
10838-5

ADAPTIVE BOILER CONTROLS BUDGETARY PROPOSAL

Manufacture: Fisher-Rosemount Inc. Representative: Karl Dittman

Technical Contact: Karl Dittman

Telephone: 708-495-8383 FAX: 708-495-0284

Equipment Name: Rosemount System 3
Network diagram sketch including key modules.

Adaptive Controller technology used: No
Attach information describing adaptive principles used and methods to build the control model. Please include expected improvements in process control over traditional PID.

Approximate number of installations. 5000

Recommended training requirements (duration) required to orient operations and maintenance staff to support and diagnose routine problems.
One week

Is the controller hardware proposed capable of supporting user developed "C" language applications? Yes

Budgetary Costs:

Equipment:	$ 128,316
Development:	$ 18,880
Commissioning:	$ 7,000
Training:	$ 7,000

Please, attach hardware and software catalog sheets.

Submitted By: Karl Dittman, System Account Manager

Date: May 5, 1993

USACERL
TYPICAL PLANT
Plant Upgrades
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ADAPTIVE BOILER CONTROLS BUDGETARY PROPOSAL

Manufacture: Moore Products Co. Representative: Stephen J. Spontak

Technical Contact: Carl L. Detterline

Telephone: 215-646-7400 FAX: 215-283-6358

Equipment Name: Mycro APACS - The Advanced Process Automation and Control Series
Network diagram sketch including key modules.

Adaptive Controller technology used: Will advise
Attach information describing adaptive principles used and methods to build the control model. Please include expected improvements in process control over traditional PID.

Approximate number of installations. New System - initial shipments in November 1992

Recommended training requirements (duration) required to orient operations and maintenance staff to support and diagnose routine problems. Approximately 2-3 weeks

Is the controller hardware proposed capable of supporting user developed "C" language applications? Yes

Budgetary Costs:

Equipment:	$ 40,000
Development:	$ 8,000
Commissioning:	$ 10,000
Training:	$ 15,000

Please, attach hardware and software catalog sheets.

Submitted By: Stephen J. Spontak

Date: 1/19/93

USACERL
TYPICAL PLANT
Plant Upgrades
10838-5

ADAPTIVE BOILER CONTROLS BUDGETARY PROPOSAL

Manufacture: Westinghouse Electric Process Control Division   Representative: Bill England

Technical Contact: Same

Telephone: 708-206-2907   FAX: 708-206-2921

Equipment Name: WDPF II

Network diagram sketch including key modules.

Adaptive Controller technology used: ______

Attach information describing adaptive principles used and methods to build the control model. Please include expected improvements in process control over traditional PID.

Approximate number of installations. ≅ 1000

Recommended training requirements (duration) required to orient operations and maintenance staff to support and diagnose routine problems. 3 man weeks (2 courses)

Is the controller hardware proposed capable of supporting user developed "C" language applications? No

Budgetary Costs:

Equipment:	$ 105,000 inc. 4 sets MANUACS
Development:	$ 36,000 inc. 8 graphics
Commissioning:	$ 960 per man day plus T&L cost
Training:	$ 3,900 ($1300/man week plus T&L cost)

Please, attach hardware and software catalog sheets.

Submitted By: [signature]

Date: January 19, 1993

Appendix D: Estimation of Hardware and Software Prices for USACERL/UI GPC Adaptive Control System

1. Microprocessor Controller

Azonix µMac-6000 Industrial Controller with Accessories

a. µMac-6000-c87	CPU, Programmable in C with 8087 Coprocessor	$3,195
b. SB-24	System Backplane, 24 Analog I/O	$ 420
c. CAB-05	Cable for COM0 to IMB PC	$ 100
d. PWR-05	5V, 20A Power Supply	$ 300
e. RM-03	Rack Mount Kit for SB-24	$ 100
f. SFT-01	IBM PC Software Support	$ 495
g. AC1843	IBM PC Driver, Manual, Cable	$ 150
h. MCCOMM-MDOS	IBM PC/XT/AT Master	$ 495
	Total:	$5,255

or

GE Fanuc Series 90-70 (Optional Choice)

a. IC697CPU781	CPU, 16MHz, 12k Discrete I/O, Expanable Memory	$4,000
b. IC697MEM715	Expansion RAM,128k Bytes, CMOS	$ 800
c. IC697CHS750	Rack, 5 Slots, Rear Mount	$ 288
d. IC697PWR711	Power Supply, 120/240 Vac, 100Watts	$ 780
	Total:	$5,868

2. Control Backup System

Control Technology's Loopmate, Model 7312, 5 @$1,195.00 each — $5,975

or

GE Fanuc Series 90-30

a. IC693CPU311	5-Slot Base with CPU (6k Byte) & Manual	$ 160
b. IC693ADS301	Cimplicity 90-ADS Package	$1,600
c. IC693PRG300	Hand Held Programmer with Cable & Manual	$ 380
	Total:	$2,140

3. Supervisory PC

Any IBM compatible 386 or 486 PC

Example, DELL 486 D/50 — $3,100

4. Intellution FIX DMACS for DOS software

150-020	SCADA Node	$2,950
250-020	Pixel Graphics	$ 500
250-030	Historical Trending	$1,000
250-090	Report Generation	$ 600
250-100	Program Scheduler	$ 300
250-050	Control Blocks	$1,250

250-060	Batch Blocks	$ 750
250-180	Standard Symbols	N/C
250-120	Historical Access	$ 250
250-150	Message Handler	$1,000
250-160	Value Trig Display	$1,000
	AD μMAC 6000	$1,500
	Total:	$11,100

For Runtime Stand Alone System

100-020R	Runtime SCADA Node	$1,950
250-020R	Runtime Pixel Graphics	$ 325
250-030R	Runtime Historical Trending	$ 650
250-090R	Runtime Report Generation	$ 400
250-100R	Runtime Program Scheduler	$ 200
250-050R	Runtime Control Blocks	$ 800
250-060R	Runtime Batch Blocks	$ 475
250-150R	Runtime Message Handler	$ 650
250-160R	Runtime Value Trig Display	$ 650
	Total:	$6,100

5. Analog Devices 5B Modules

a. 5B39, 0 - 20 mA Output module, 5, each @$150.00	$ 750
b. 5B32, Current Input Module, 10, each @$150.00	$1,500
Total:	$2,250

6. Software for C code development and Compiler.
   a. Quick C, V2.5 or higher
   or
   b. Aztec C86 Compiler, v4.2 or higher — $1,000

7. Uninterruptable Power Supply (for example, Superior Electric Company Model UPS61005R Stabiline). — $ 450

8. Boiler Instrument Upgrade

Device	Vendor	Equip Cost	Hr	Matrl & Ins Cst	Total Cost
Steam Pressure Xmtr	Rosemount	$ 565	4	$ 300	$ 865
Drum Level Xmtr w 3-valve Man.	Rosemount	$ 1,100	8	$ 600	$ 1,700
Steam Flow Xmtr w 3-valve Man.	Rosemount	$ 1,100	4	$ 300	$ 1,400
Feedwater Flow Xmtr	Nice	$ 1,125	8	$ 600	$ 1,725
Feedwater Control Valve	Fisher	$ 1,850	4	$ 300	$ 2,150
Auto-Manual Station	CTI	$ 895	0	$ 0	$ 895
Fuel Gas Flow Transmitter	Nice	$ 1,125	8	$ 600	$ 1,725
Gas Valve Actuator	Fisher	$ 750	4	$ 300	$ 2,150
Auto-Manual Station	CTI	$ 895	0	$ 0	$ 895
Air Flow Element & Xmtr	Sierra	$ 2,025	8	$ 600	$ 2,625
Oxygen Analyzer	Bailey	$ 3,129	8	$ 600	$ 3,729
Air Damper Actuator	Bailey	$ 1,150	4	$ 300	$ 1,450
Auto-Manual Station	CTI	$ 895	0	$ 0	$ 895

24 volt DC Power Supply	$ 300			$ 300
Misc. Electrical Material	$ 600	32	$2,400	$ 3,000
Total:	$17,504			$27,404

9. Budgetary Costs:

a. Equipment: (with boiler instrument upgrade costs)	$51,534
(Without boiler instrument upgrade costs)	$24,130 *
b. Development: Mainly the software development and tests	$30,000
c. Commissioning:	$10,000
d. Training: 2 weeks, $100/Hr,	$ 8,000
Grand Total	$99,534
(Without boiler instrument upgrade)	$72,130 *

* Values used for comparison in Economic Evaluation in Chapter 4, Competitive Control Systems.

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